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Effect of Frictional Treatment on the Microstructure and Surface Properties of Low-Carbon Steel

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Abstract. The microstructure of annealed low-carbon (0.17 wt% C) steel subjected to frictional treatment with a sliding hard-alloy indenter is studied by EBSD analysis, as well as its micromechanical characteristics. It has been found that frictional treatment results in high dispersity of the structure in the steel surface, down to the submicro- and nanocrystalline state. Instrumented microindentation has revealed that, under all the loads, the values of the contact elastic modulus E^* of low-carbon (0.17 wt% C) steel after frictional treatment are lower than those in the initial annealed state. Particularly, the mean value of E^* decreases from 208 to 168 GPa under a load of 1 gf on the indenter, from 213 to 176 GPa under a load of 25 gf and from 204 to 155 GPa under a load of 200 gf. It is for the first time that the effect of a decrease in the elastic modulus is observed for a carbon steel subjected to frictional treatment. It also follows from the microindentation data that frictional treatment increases the capability of the surface of annealed low-carbon (0.17 wt% C) steel to withstand higher contact loads prior to plastic deformation.

INTRODUCTION

Surface plastic deformation methods are widely used to improve the operational properties of the surfaces of metals and alloys. As applied to such low-strength and ductile materials as, e.g., annealed low-carbon and stainless austenitic steels, surface deformation processes allow products with a low-strength bulk, high surface hardness and wear resistance (gears, worm screws, pipeline accessories, etc.) to be produced. A method for surface plastic deformation is selected on the basis of the need to reach the best quality, applicability to the chosen materials and in view of specific process conditions. Particularly, frictional treatment with a sliding indenter is an effective way of nanostructuring the surface layers of practically any metal materials, including high-strength and hard-to-deform alloys. Nanocrystalline layers formed by frictional treatment can be viewed as a “natural” coating, differing greatly from the base material in their morphological features and structure imperfection, their physical-mechanical and other properties.

When materials are hardened by severe surface plastic deformation, it is important to evaluate the strength and plasticity of the surface layer and its ability to withstand contact loads and resist fracture. The testing of the properties of modified surface layers requires a local way of loading, which can be implemented through indentation. The parameters H_{IT}/E^* [1], R_e [2, 3] and H_{IT}^3/E^{*2} [4] are determined with the use of characteristics measured directly during indentation, by which it is possible to evaluate the ability of various materials to resist mechanical contact effects [5, 6], including wear [7-9], and, consequently, to withstand service loads. The higher the values of the above-mentioned parameters, the greater the ability of a material to withstand higher contact loads prior to plastic deformation. The aim of this paper is to study the structure and micromechanical characteristics of annealed low-carbon (0.17 wt% C) steel subjected to frictional treatment with a sliding indenter.

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EXPERIMENTAL PROCEDURE

Commercial low-carbon steel GOST 20 (in wt. %: 0.17 C, 0.41 Mn, 0.13 Si, 0.040 Cr, 0.057 Ni, 0.019 S, 0.020 P, 0.034 Cu, Fe for balance) was studied. To produce an equilibrium structure, the steel was annealed at a temperature of 800 °C for 8 h and then cooled in a furnace. The heat-treated specimens were electrolytically polished in an acetic chlorine electrolyte (90%CH_3COOH+10%$HClO_4$). The frictional treatment of 3 mm thick flat specimens was performed in air by means of reciprocating sliding with a cylindrical hard-alloy indenter having a diameter of 10 mm at a load of 690 N, an average sliding velocity of 0.06 m/s and the number of reciprocal sliding cycles of the indenter equal to 300. A scheme of the frictional treatment is presented in [10, 11]. The microstructure of the steel was examined using a Tescan VEGA II XMU scanning electron microscope (SEM) with Advanced AZtec HKL EBSD analysis system. Instrumented microindentation with loading curve recording was performed on a Fischerscope HM2000 XYm measuring system using a Vickers indenter and the WIN-HCU software at maximum loads of 0.0098 N (1 gf), 0.245 N (25 gf) and 1.96 N (200 gf), according to ISO 14577.

RESULTS AND DISCUSSION

Figure 1 shows the results of studying the structure of annealed low-carbon (0.17 wt% C) steel before and after frictional treatment. It is obvious that the annealed steel has a coarse-grained structure (Fig. 1a, b) and that its ferrite grain size ranges between 2 and 35 μm, the average size being about 12 μm (Fig. 1c). Friction treatment results in high dispersity of the structure in the surface layer of the annealed low-carbon (0.17 wt% C) steel (Fig. 1d, e), which is caused by severe deformation by friction. The minimum ferrite grain size in a 5 μm thick deformed layer is about 200 nm, the average grain size being about 800 nm (Fig. 1f), and this testifies to the refinement of the structure, down to the submicro- and nanocrystalline state, which agrees with the data of transmission electron microscopy [11]. Note that no prevailing orientations have been found both for the initial annealed steel (Fig. 1a) and for the steel after frictional treatment (Fig. 1d). The presence of zero solutions (white portions in Fig. 1d, e) on the EBSD maps of the steel after frictional treatment may be due to a high level of stresses arising from significant lattice microdistortions under large amounts of strain in the friction surface [11].

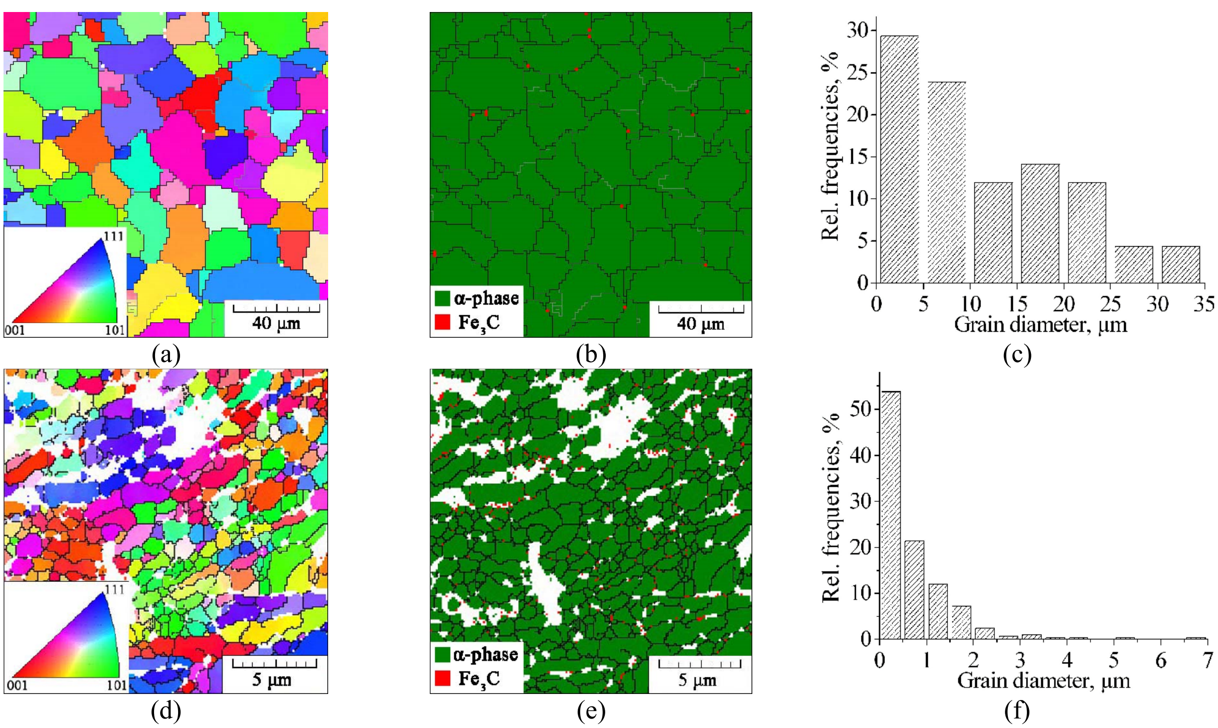

FIGURE 1. EBSD IPF-Z maps (a, d), phase maps (b, e) and grain size frequency diagrams (c, f) for the low-carbon (0.17 wt% C) steel in the initial annealed state (a-c) and after the frictional treatment (d-e)

Table 1 presents data on instrumented indentation under different loads on the indenter, from which it follows that the frictional treatment of the annealed low-carbon (0.17 wt% C) steel decreases the values of the maximum and permanent indentation depths h_{max} and h_p, increases Martens hardness HM and indentation hardness at the maximum load H_{IT}. Besides, there is an increase in the elastic reverse deformation work of indentation W_e and a decrease in the total mechanical work of indentation W_t. This change in the characteristics measured during indentation testifies to surface hardening is typical of frictional treatment [6]. However, under all the loads, the values of the contact elastic modulus E^* for the low-carbon (0.17 wt% C) steel after frictional treatment are 17-24 % lower than those for the initial annealed state (see Table 1). This may be caused by the change in the structural-phase state and, particularly, by increased dislocation density in the surface layer of the steel after frictional treatment [12]. The elasticity moduli of metallic materials of the same chemical composition are structurally low-sensitive properties with few exceptions (see, e.g., [13]). For a carbon steel subjected to frictional treatment, the decrease in the elastic modulus is observed for the first time. It was previously observed that the frictional treatment under certain conditions decreases the contact elastic modulus E^* of austenitic stainless steel, however, the decrease is less than 8 % [14].

TABLE 1. Surface microindentation results at the different maximum loads on a Vickers indenter P for the low-carbon (0.17 wt% C) steel in the initial annealed state (A) and after the frictional treatment (FT)

P, gf	Processing	h_{max}, µm	h_p, µm	HM, GPa	H_{IT}, GPa	E^*, GPa	W_e, nJ	W_t, nJ
1	A	0.43±0.03	0.41±0.03	2.1±0.1	2.3±0.1	208±7	0.128±0.004	1.577±0.051
	FT	0.27±0.04	0.21±0.06	5.5±0.5	7.4±1.0	168±15	0.291±0.034	0.935±0.038
25	A	2.57±0.13	2.41±0.16	1.5±0.1	1.6±0.1	213±4	13.0±0.2	211.4±3.9
	FT	1.65±0.27	1.35±0.35	3.7±0.5	4.5±0.7	176±10	26.5±2.3	141.4±7.8
200	A	8.07±0.20	6.98±0.28	1.23±0.02	1.29±0.02	204±8	283±8	5285±88
	FT	5.41±0.45	4.53±0.54	2.7±0.1	3.2±0.2	155±4	554±21	3635±158

Besides, parameters characterizing the ability of the surface to resist mechanical contact action, which are presented in Table 2, have been determined from the characteristics measured during indentation. Elastic recovery $R_e=((h_{max}-h_p)/h_{max})\times100\%$ and the ratios H_{IT}/E^* and H_{IT}^3/E^{*2} are seen to increase considerably due to the frictional treatment of the annealed low-carbon (0.17 wt% C) steel. The most significant increase is observed at the minimum load on the indenter, when a thin surface layer is analyzed, which has maximum hardness [10, 11] and dispersity of structure. It is important to note that the increase of the above-mentioned ratios stems not only from increased indentation hardness H_{IT}, but also from the here-found lower value of the contact elastic modulus E^* of the low-carbon (0.17 wt% C) steel after frictional treatment.

TABLE 2. The parameters R_e, H_{IT}/E^* and H_{IT}^3/E^{*2} at different maximum loads on a Vickers indenter P for the low-carbon (0.17 wt% C) steel in the initial annealed state (A) and after the frictional treatment (FT)

P, gf	Processing	R_e, %	H_{IT}/E^*	H_{IT}^3/E^{*2}, GPa
1	A	6.7	0.011	0.00028
	FT	25.2	0.044	0.01449
25	A	6.1	0.008	0.00009
	FT	18.5	0.026	0.00292
200	A	13.5	0.006	0.00005
	FT	16.4	0.020	0.00132

Thus, it follows from the microindentation data that frictional treatment increases the ability of the surface of the annealed low-carbon (0.17 wt% C) steel to withstand higher contact loads prior to plastic deformation. The elevated resistance of the surface layer nanostructured by frictional treatment to elastic and plastic deformation hampers the processes of microcutting, seizure and plastic edging in wear and causes a considerable growth of the wear resistance of quenched medium-carbon (0.51 wt% C) steel tested under conditions of abrasive wear and sliding friction [7]. Therefore, one can expect that frictional treatment will also increase the wear resistance of annealed low-carbon (0.17 wt% C) steel under various wear conditions.

CONCLUSIONS

It has been established by EBSD analysis that the initial ferrite-pearlite structure of annealed low-carbon (0.17 wt% C) steel is characterized by the ferrite grain size ranging between 2 and 35 μm, with an average grain size of about 12 μm. Frictional treatment results in high dispersity of the structure in the steel surface, which is caused by severe deformation by friction. The minimum grain size in the deformed 5 μm thick layer is about 200 nm, this being indicative of structure refinement down to the submicro- and nanocrystalline state. The results of instrumented microindentation with a Vickers pyramid with different loads on the indenter testify that, at all the loads, the values of the contact elastic modulus E^* of low-carbon (0.17 wt% C) steel after frictional treatment are lower than those for the initial annealed state. Particularly, the mean value of E^* decreases from 208 to 168 GPa when the load on the indenter is 1 gf, from 213 to 176 GPa when the load is 25 gf and from 204 to 155 GPa when it is 200 gf. This may be due to a change in the structure-phase state and, in particular, to increasing dislocation density in the surface layer of the steel after frictional treatment. For the carbon steel subjected to frictional treatment, the decrease in the elastic modulus is observed for the first time. The results of microindentation have also shown that, after frictional treatment, the ratio H_{IT}/E^* increases from 0.011 to 0.044 (with a load of 1 gf), from 0.008 to 0.026 (with a load of 25 gf) and from 0.006 to 0.020 (with a load of 200 gf); elastic recovery R_e grows from 6.7 to 25.2% (with a load of 1 gf), from 6.1 to 18.5% (with a load of 25 gf) and from 13.5 to 16.4% (with a load of 200 gf); the power ratio H_{IT}^3/E^{*2} increases from 0.00028 to 0.01449 GPa (with a load of 1 gf), from 0.00009 to 0.00292 GPa (with a load of 25 gf) and from 0.00005 to 0.00132 GPa (with a load of 200 gf). This testifies that frictional treatment enhances the ability of the surface of annealed low-carbon (0.17 wt% C) steel to withstand elevated contact loads prior to plastic deformation.

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